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Detection of displacements on Tenerife Island, Canaries, using radar interferometry

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SUMMARY

Tenerife is one of the most well monitored islands of the Canaries, but the surveillance generally is centred on Las Cañadas Caldera, where the Teide volcano is located. In the last 180 000 yr, the eruptions on Tenerife Island have never occurred in the same volcanic structure, except for the Teide and Pico Viejo central volcanic system, so that a complete monitoring network would have to cover the whole island. As a result, Synthetic Aperture Radar Interferometry (InSAR) is being used on Tenerife, because this space technique can provide a displacement map of the surface of the earth with centimetre precision. This paper presents the results obtained on Tenerife Island using 18 SAR images acquired by the ERS-1 and ERS-2 satellites during the period 1992–2000. Two important results have been obtained: no deformation on Las Cañadas Caldera, coinciding with results obtained using terrestrial techniques, and two subsidence episodes outside monitoring areas in the NW of the island, in the region of the last historic eruptions. These results show that InSAR is a useful technique for monitoring the entire island, thus allowing us to discover deformations in areas that are not routinely or easily monitored. This technique has been used in combination with Global Positioning System (GPS) observation of a global network on the island to define a new geodetic monitoring system. The possible causes of the deformations observed have been studied in an endeavour to discern if they might be of natural origin, in particular linked to a reactivation of prior volcanic activity. Examination of the geophysical observations on the island, human activities underway and the results of the modelling seem to indicate that at least part of the deformations may be caused by changes in the groundwater level and therefore are not linked to a volcanic reactivation. This result is important because it implies that, if geodetic volcano monitoring is to be performed on the island, the system used must be capable of discerning between various possible origins of the deformation by analysing their patterns and ancillary information from other sources. In this regard, InSAR is a basic tool on account of its unpaired wide area coverage and spatial density.

Key words: crustal deformation, geodesy, groundwater level, SAR interferometry, Tenerife, volcano monitoring.

1 INTRODUCTION

As described extensively in the existing bibliography, volcanic activity often is manifested on the surface as ground deformation and gravity changes, which are eruption precursors in some cases. Consequently, the traditional monitoring systems based on the use of seismic, hydrologic, or fumarolic activity observations have been complemented with geodetic observations (see e.g. Sigurdsson *et al.* 2000). Geodetic techniques are being used extensively at active volcanoes (see e.g. Fiske & Shepherd 1990; Dvorak & Dzurisin 1997; Segall & Davis 1997; Fernández *et al.* 1999; Sigurdsson *et al.* 2000;

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Yu *et al.* 2000) and ground deformation measurement techniques are proving a powerful tool for understanding the volcanic cycle. Geodetic volcano monitoring includes the deployment of long-term instrumentation, such as clinometers and extensometers, and regular geodetic network surveying campaigns using classic terrestrial techniques or Global Positioning System (GPS). Radar interferometry technology can be highly useful in this context, as it is a suitable tool for ground deformation monitoring of active volcanic areas (see e.g. Massonnet & Feigl 1998; Bürgmann *et al.* 2000; Hanssen 2001). A key issue is that, whereas geodetic surveying measurements only provide information about certain selected points, Synthetic Aperture Radar Interferometry (InSAR) images provide areas of 100 × 100 km, detailing 2-D deformation trends throughout the whole area of interest and its surroundings, permitting the extrapolation of the field measurements and the analysis of areas beyond the reach of the field deployed instrumentation.

In general, major eruptions are associated with polygenetic volcanoes, i.e. central volcanoes or stratovolcanoes with recurrent eruptions in the same volcanic structure, the area to be monitored usually being well defined. However, it becomes harder to predict future eruptions when their likelihood is not limited to a specific volcano but to a wide active volcanic region. This is the situation in the volcanic area of Tenerife, where there is an important stratovolcano, Teide, but the last historic eruptions (500 yr ago) did not occur repeatedly in the same volcanic structure, but occurred at various locations around the island.

Tenerife, Fig. 1, is the biggest island of the Canarian Archipelago. Its eruptive system is dominated by the Las Cañadas Caldera (Martí *et al.* 1994) and Teide, a 3715-m stratovolcano located at the northern border of this caldera and formed over the last 150 000 yr (Martí *et al.* 1994; Ablay & Martí 2000). Las Cañadas Caldera and Teide form the area where almost all volcanic research has been conducted, in particular geodetic measurements in the southern part of the caldera where a geodetic micronetwork and a levelling network have been installed (Sevilla & Sánchez 1996; Sevilla *et al.* 1996). Prior to 2000, different authors have conducted seismic studies (Almendros *et al.* 2000), several gravimetric campaigns for structural studies (Vieira *et al.* 1986; Ablay & Keary 2000; Araña *et al.* 2000a), temporary observations of gravimetric tides (Arnoso *et al.* 2000), regular observations of temperature, fumarolic activity and measurements of different gases emitted at the top of Teide (González *et al.* 2000; Salazar *et al.* 2000) and diffusive degassing in and around the caldera (Hernández *et al.* 2000). These observations have not detected any clear anomaly that can be regarded as indicating volcanic reactivation in the monitored areas.

However, the fact that both recent volcanic activity (Carracedo *et al.* 2003) and historic volcanoes, see Fig. 1, on the island are very scattered (see e.g. Fernández *et al.* 2003) indicates that techniques capable of covering the whole island should be used, otherwise possible anomalies associated with future eruptions might not be detected, as pointed out by Yu *et al.* (2000). In this context, research and pre-operational projects were developed to try to demonstrate the feasibility of using InSAR for operational decision-making support purposes in a volcanic risk scenario such as the Canary Islands and to define a monitoring system for volcanic hazard in Spain that includes the operative use of these techniques (see Carrasco *et al.* 2000a,b; Fernández *et al.* 2002). These projects were designed to ascertain whether or not any deformation occurred in the period in question, 1992–2000, in particular in the zones not covered with the traditional methods of geodetic surveillance. This paper describes the results obtained on the island of Tenerife using 18 SAR images acquired by the satellites ERS-1/2 of the European Space Agency

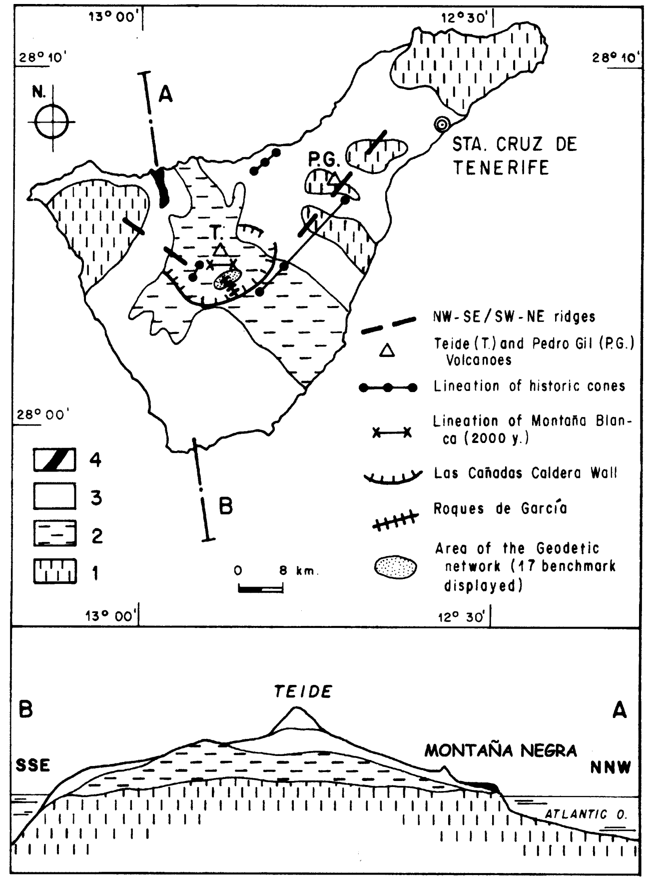


Figure 1. Geographical and geological information. Upper panel, geological sketch of Tenerife Island: 1, ancient basaltic series; 2, Cañadas series; 3, recent and historical series; and 4, 1706 Montaña Negra eruption lava flows. Also shown is the location of the Tenerife ridges and the geodetic network. Roques de García is a spur between the two calderas. Lower box, geological section (A–B) showing the position of the Teide complex and Montaña Negra volcano. Positive latitude to the N and positive longitude to the W in the figure (modified from Fernández *et al.* 2003).

(ESA), as well as a discussion and comparison with the results obtained with other geodetic observation methods. It also describes the modelling and interpretation of the results, and their repercussion on routine monitoring of possible volcanic reactivation on the island.

2 VOLCANIC ACTIVITY ON TENERIFE ISLAND

The historic volcanism of Tenerife (over the past 500 yr) consists of a total of six eruptions (Solana 1998; Fig. 1). The largest concentration is found on the ridges of the island, along NW–SE and SW–NE structural axes. 3.5 Myr ago (Martí *et al.* 1994) volcanic structures arose at the intersection of the two ridges and subsequently collapsed (0.2 Myr ago), generating the Las Cañadas depression. It was on the northern edge of this depression that the Teide—Pico Viejo complex, which remains active today (albeit restricted to fumarolic emissions), began to form 150 000 yr ago. The oldest of the historic eruptions occurred in 1430 (Taoro) and the lava flowed into the La Orotava valley from three different points. The next eruption took place through a relatively extensive fracture, several kilometres wide, with lava flowing from three separate places, Siete

Fuentes (1704 December), Fasnia (1705 January) and Arenas (1705 February). The Montaña Negra volcano arose in 1706 May, with lava flows that reached the sea in just a few hours. The Chahorra eruption took place in 1879, on the slopes of the Teide—Pico Viejo complex, and is the longest eruption on record, having lasted nearly 3 months, and its lava flows occupied an extensive surface of the of Las Cañadas depression. The last eruption, Chinyero, took place in 1909 near Chahorra and Montaña Negra and was the shortest on record (9 days). There are signs of other subhistoric eruptions, such as certain pre-Columbian eruptions calculated to have taken place in 1341, 1396 and 1444 (Araña *et al.* 2000b), although there is not enough information to characterize them completely. The eruptions of the Media Montaña and Güimar volcanoes to the south of the island and of Montaña Blanca appear to be recent, though not historic.

Broadly speaking, all the eruptions listed above are similar in nature, being strombolian-type monogenetic eruptions that generate structures no more than 300 m high. The volume of material released is very small, with small lava flows and eruptions that last between a few days and 3 months. Most of the materials released are of a basaltic nature, which sometimes evolve from olivine to amphibolous facies and more seldom to intermediate facies (Solana 1998), giving rise to changes in the viscosity, which seems to affect how fast these lava flows reach the sea.

The felsic-plinian eruptions are another type of dangerous volcanism associated with the central edifice of Las Cañadas caldera. It is non-historic volcanism and its deposits correspond to pyroclastic flows and ignimbritic rocks of phonolitic composition emitted during three cycles between 1.57 and 0.179 Ma (Martí & Gudmundsson 2000). These materials are represented by the stratigraphic level named 'Bandas del Sur' (Alonso *et al.* 1988), occupying a huge zone on the south of the island. The last salic explosive eruption occurred in Montaña Blanca in the Teide slopes, 2000 yr ago (Ablay *et al.* 1995). For this reason, we also must consider the possibility of eruption in the area of this emission centre.

This last type of volcanic activity alone would justify the definition of a geodetic monitoring system to be implemented in a more broad approach to the volcanic monitoring in the island, including other techniques (e.g. seismology and geochemistry). Considering as well the recent volcanic activity, this monitoring system must be capable of covering the whole island, not only the area of Las Cañadas caldera.

3 SENSITIVITY TEST RESULTS FOR THE LAS CAÑADAS GEODETIC SYSTEM

In the past, traditional geodetic monitoring of volcanic activity in Tenerife could not be designed to cover the whole island, and instead focused on La Caldera and the Teide and Pico Viejo volcanoes, on the assumption that, with limited resources, the risk was minimized by monitoring these zones. Until recently, systematic monitoring of the whole island was discarded as a result of the high costs involved and the limited risk.

Yu *et al.* (2000) used a theoretical model to conduct a sensitivity test of the geodetic network in the Las Cañadas Caldera. This model (Okada 1985) uses a realistic source, a dyke, as in Tenerife most basaltic eruptions have been fed by dykes (Marinoni & Gudmundsson 2000). They changed the depth and location of the dyke to study the variation of the displacements produced. They found that the size and location of the intruded dyke plays a major role in determining both the displacement pattern and magnitude. When the dyke is close to the surface, there is an inversion of the surface displacement pattern and very large surface displacement at certain benchmarks. Such phenomena could serve as precursors of such dyke eruptions. Their study clearly shows the need to extend the existing geodetic network to cover the full island for volcano monitoring purposes. Obvious options are a GPS network, the use of InSAR or a combination of both techniques. Taking all this into consideration, the InSAR technique was regarded as a good option for global surveillance of the island.

4 APPLICATION OF INSAR IN TENERIFE

With the launch of the ERS-1 (1991) and ERS-2 (1995) satellites from the ESA and the further developments in radar processing, InSAR began to be used for ground deformation measurement. This technique exploits the properties of coherent radar images to make centimetre differential measurements between two different dates of the satellite-to-ground distance, thanks to accurate phase measurements at microwave frequencies (see e.g. Massonnet 1997; Massonnet & Feigl 1998; Rosen *et al.* 2000; Hanssen 2001). Typically, with the ERS satellites, a ground deformation of 28 mm results in a 2π phase shift, or a fringe, in the interferogram. In practical cases, we are able to deliver blanket coverage, with a density up to four measurements per hectare (after spatial filtering to reduce noise) over a 100×100 km area, which is the typical satellite image size. Space-borne radar sensors behave like an electronic distance meter capable of making a measurement update of an area under study every 35 days, which is the time it takes for a satellite to revisit the same zone. The key benefit is the possibility to provide the 2-D perspective of the deformation trends over large areas and long time spans. An additional advantage is the availability of a huge worldwide data archive from the ERS satellites that enables a retrospective study of ground deformation without any fieldwork; since 1991, the data has been recorded by an ESA scientific background mission and much of it remains unexploited.

The major limitations of the technique are associated with phase noise, or coherence degradation over vegetated areas or surfaces whose microwave backscattering is not stable over time (temporal decorrelation; e.g. Massonnet & Feigl 1995). Typical volcanic landscapes covered with lava and exposed rocks are well suited for the application of differential InSAR. The second limitation is associated with changes in atmospheric propagation conditions, which, if not properly isolated, can be mistaken for ground displacement (e.g. Hanssen 2001). The main atmospheric factors that appear superimposed on the deformation patterns in the interferograms are water vapour content and atmospheric layering (pressure and temperature), sometimes associated with topography (e.g. Puglisi & Coltelli 2001).

As a prerequisite to our study and as a key step to ensure the feasibility of the technique for operational monitoring in our scenario, we needed to assess that the interferometric coherence was high enough to enable ground deformation measurement over long time spans (years). If the surface of the island remains coherent, the differential interferograms and the fringes that may appear in them can be studied in an endeavour to determine their origin: ground displacements (that may be associated with new volcanic activity) or phase artefacts (caused by a poor quality digital elevation model, DEM, by atmospheric interferences, etc.). Our study of Tenerife was based on 18 images (Table 1), acquired by the ERS satellites of the ESA from 1992–2000 and that were selected in accordance with the following criteria.

Table 1. ERS images from track 352 and frame 3036 used in the Tenerife study. All were acquired from the descending pass. No. indicates the asigned number to each image, SAT denotes the satellite, E1 is ERS-1 and E2 is ERS-2. Perpendicular baseline ($B_\perp$) refers to the 1992 May 26 image.

No.	SAT	ORBIT	DATE	TIME	$B_\perp$
1	E1	21382	17-08-95	11:42	578
2	E2	1709	18-08-95	11:42	489
3	E1	4505	26-05-92	11:41	0
4	E1	10517	20-07-93	11:42	287
5	E1	20380	08-06-95	11:42	458
6	E1	20881	13-07-95	11:42	146
7	E1	21883	21-09-95	11:42	241
8	E1	22885	30-11-95	11:42	246
9	E2	6218	28-06-96	11:42	494
10	E2	6719	02-08-96	11:42	472
11	E2	7220	06-09-96	11:42	150
12	E2	11228	13-06-97	11:42	372
13	E2	14234	09-01-98	11:42	358
14	E2	17240	07-08-98	11:42	658
15	E2	26759	02-06-00	11:41	642
16	E2	28262	15-09-00	11:41	460
17	E2	28763	20-10-00	11:41	400
18	E2	29765	29-12-00	11:41	125

(i) Baseline: the spatial distance between the two points of space from which we obtain the two SAR images projected perpendicular to the line of sight. The perpendicular baseline ($B_\perp$) ranges from a few metres to hundreds or even thousands of metres. The perpendicular baseline must never exceed 1200 m (theoretical critical baseline in interferometry for the ERS over flat terrain), because the phase differences in the two images would be too large to obtain a clear interferogram. In practice, smaller baselines are used. We studied the island of Tenerife by combining images with a perpendicular baseline of less than 350 m.

(ii) Selection of images in the driest months: in order to minimize temporal decorrelation, most images were selected out of the winter season, the months when Teide is likely to be covered in snow.

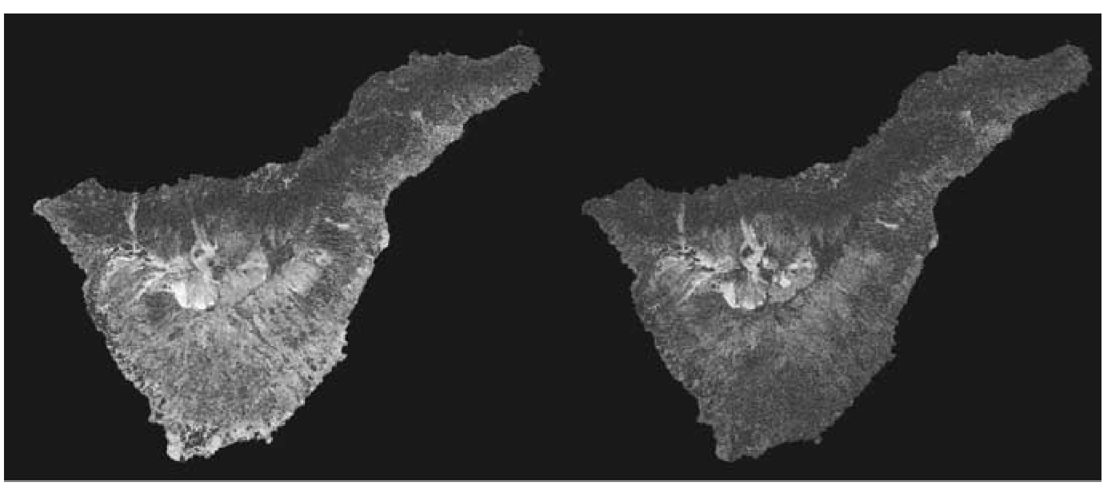
(iii) Images evenly spaced in time: the goal was to demonstrate that InSAR could be applied to monitoring volcanic activity on Tenerife, so we endeavoured to obtain images of every year from 1992 to 2000, in order to have temporal sampling of what occurred during each year.

The selected SAR images were processed with the EPSIE software developed by Indra Espacio (Martínez & Moreno 1997). The differential interferograms were generated with an external DEM, with a resolution of 25 m, which enables accurate correction of the topographic components in the mountainous island for whatever the baseline.

The use of an ancillary DEM, instead of correcting the topographic phase from additional InSAR data (such as 1-day spaced ERS-1/2 Tandem data), reduces the impact of atmospheric artefacts. This DEM is provided commercially by the Instituto Geográfico Nacional Centro Nacional de Información Geográfica (IGN-CNIG) and it is a standard product available over all the Spanish territory. It is obtained from the restitution level curves, as well as all the bounded points and break lines (watercourses, watersheds, etc.). A 25-m grid is applied to these 3-D files with the Stuttgart Contour Software (SCOP) programme, which uses the least-squares–collocation method. The quality of the Mapa Topográfico Nacional (MTN) 25 can be estimated as 4.5 m of standard reliability.

We have obtained 21 differential interferograms, see Table 2, from the 18 SAR images. There follows a brief description of technical results.

(i) Coherence: Tenerife coherence images have shown that the surface of certain parts of the island has remained stable over long periods of time (up to 7 yr). The coherence is to be seen above all in the area of Las Cañadas Caldera and the ridges (Fig. 2), in those regions where the last eruptions took place and that, according to recent studies (Araña *et al.* 2000b), pose the main volcanic hazard in line with the type of volcanism of the island. The high coherence obtained in these areas is a result of the fact that they are covered by the lava of the different eruptions with little or no vegetation and that remains stable. The southern part of the island is also coherent in most of the images obtained, depending on the $B_\perp$ and the time that has elapsed between them. Fig. 2 displays examples that show the variation in coherence on the island for different $B_\perp$ and days. The smaller the time interval and the shorter the baseline



(a) (b)

Figure 2. Coherence images of Tenerife, showing how the coherence decreases as number of days between images (Δd) increases. (a) 13Jun97–9Jan98; $B_\perp = 14$ m; $\Delta d = 210$ days. (b) 2Aug96–15Sep00; $B_\perp = 8$ m; $\Delta d = 1505$ days. $B_\perp$ denotes perpendicular baseline.

Table 2. Pairs of images used to obtain the 21 interferograms using the 18 images indicating the perpendicular baseline in metres. No. is the assigned number to every image given in Table 1.

No.	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
3	287														
4			140		40			136	86	72		347	180		162
5									85	99		184			
6								4							
7															
8															
9															
10									101		185		8		
11															
12										14				28	
13											301				
14												23			
15													168		

between the two images, the greater is the coherence of the interferogram (Fig. 2a). High coherence ensures a clear interferogram and better detection of any displacement that might occur on the surface of the island. The least coherent areas of the island are in the north, from Punta Teno in the west to Punta de Anaga in the east. The centre of the island is surrounded by a vegetation ring (pine trees), making it hard to obtain accurate phase measurements, even with a short lapse of time between each image (Fig. 2a).

(ii) Differential fringes: the 21 differential interferograms obtained showed fringes. An interpretation of these is needed to distinguish between deformation and atmospheric errors. Whereas big deformation patterns (over two cycles in a single interferogram) are easily evidenced, small deformations about one phase cycle can be confused with atmospheric interference and require more than one interferogram to be confirmed. In practice, this has to be done by comparing interferograms from different dates with a common time span or time-series. Next we describe the interpretation of the interferograms.

All the interferograms with a time interval of more than 7 months show concentric fringes in the northwestern part of the island (Montaña Negra deformation in Garachico: Fig. 3, panel 1), approximately 4 km to the south of Garachico, where the Montaña Negra volcano lava flow (1706; Fig. 1) reached the port of the town. The lava flow is surrounded by pine forests and undergrowth (brushwood and shrubs). The vegetated areas are not coherent enough and are degraded even in a tandem interferogram (1-day separation), masking the deformation outside the lava flow. The interferograms with a time interval of more than 4 yr and those processed with images from 1998 to 2000 show an additional deformation pattern with a fringe attributable to a second deformation to the south of the aforementioned one (Chío deformation: Fig. 3, panel 2), in an area of the NW–SE ridge also covered by volcanic material. The hypothesis that these fringes were the result of atmospheric interference was discarded because they appeared in independent interferograms (i.e. interferograms that did not have any images in common and included the same time span) and the number of fringes seemed to increase linearly with the interval of time between the images that formed them (Fig. 3, panel 3). Both deformations correspond to a small ground subsidence. The three fringes in the Garachico deformation are equivalent to 8.4 cm in the LOS and, considering all the deformation is vertical displacement, to 9.1 cm of subsidence between 1992 and 2000, over an area approximately 15 km^2. There is one fringe in the Chío deformation, equivalent, with the same assumptions as before, to a subsidence of 3 cm between 1992 and 2000, over an area approximately 8 km^2. The Garachico deformation has evolved more steadily, by approximately 1 cm yr^{-1} since 1992, whereas the Chío deformation was almost the same size in 1992–1998 as in 1998–2000 and seems to have increased more in the latter period (Fig. 3, panel 3).

The most closely monitored area of the island, Las Cañadas Caldera, has different fringes in most of the interferograms, albeit without the same pattern, suggesting that they are of atmospheric origin. In addition, in several interferograms (e.g. Fig. 4, panel 4) the area appears flat (without fringes), indicating the absence of deformations. Therefore, we can conclude that there was no significant displacement in the Las Cañadas Caldera, at the centimetre level, between 1992 and 2000. This result coincides with those obtained from the observations conducted in the La Caldera networks from 1984 to 2000 (Fernández *et al.* 2003).

All the Tenerife differential interferograms show, to a greater or lesser extent, interference (more than two fringes in some cases) that cannot be attributed to deformation, or to DEM errors (discarded beforehand as a result of the quality of the DEM used), but to atmospheric errors. The two main causes of atmospheric errors are topography and the tropospheric water vapour content. Tenerife is a clear example of the problem that arises when there is an uneven topography in the area to be studied with InSAR (3715 m top height in Teide volcano). Several differential interferograms display concentric fringes surrounding La Caldera de Las Cañadas. Fig. 4 (panel 4) displays one of these interferograms, which contains two of these fringes. If these were misinterpreted as ground displacements, it would indicate that the centre of the island had risen 6 cm between 1997 and 1998, which would have been noticed in the concurrent field observations made on the island and, of course, in the other interferograms. The other interferences that appear in the differential interferograms and that cannot be attributed to deformation or to topographical-type atmospheric errors have also been associated with atmospheric errors because they seem to be caused by the particular phase pattern of a particular image. Fig. 4 displays three differential interferograms that have in common the image of 9 January 1998 and a similar pattern of interference in the western part of the island (visible when the coherence permits it), which is assumed to be caused by the atmospheric components in the image. Again, if only these InSAR images were available for analysis, the Chío deformation would have been masked by the atmospheric errors. Based in our experience, slight deformations down to one cycle (like the one in Chío) can be detected by an experienced eye in the middle of atmospheric interference as far a SAR multiple observations are available over time.

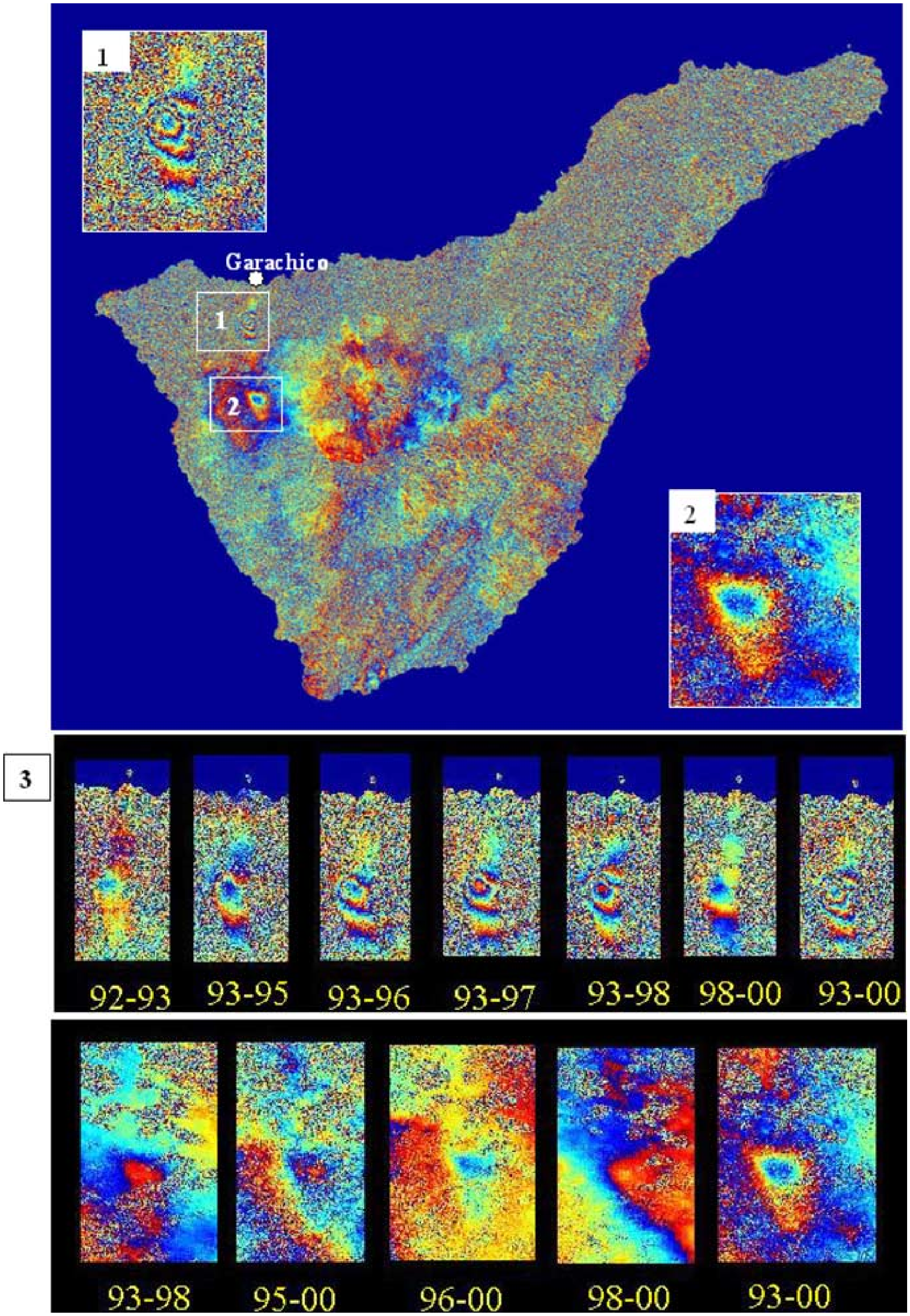


Figure 3. Differential interferogram of Tenerife, processed with 1993 July 20 and 2000 September 15 images: panel 1, Garachico deformation (three fringes); panel 2, Chío deformation (one fringe); panel 3, cuttings/clippings of several differential interferograms of Tenerife, showing how the subsidence evolves in time. Above, Garachico deformation; below, Chío deformation.

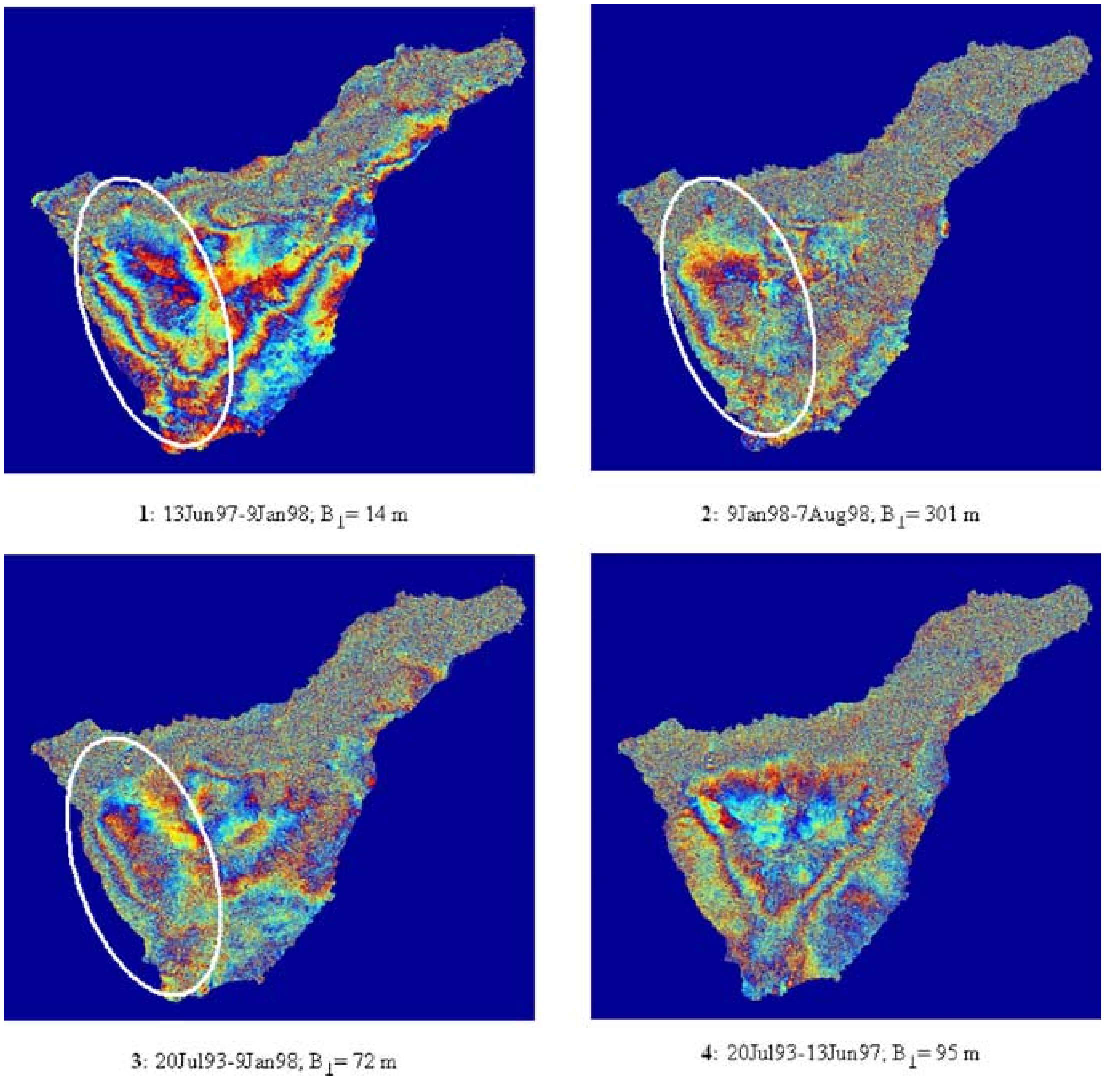


Figure 4. Differential interferograms of Tenerife. Images in panels 1, 2 and 3 have in common the 1998 January 9 image, thus atmospheric effects in this image must cause the interference on the western part of the island (marked in white), the pattern being very similar in all four images. The image in panel 4 shows fringes correlated with the topography and flat phase over Las Cañadas Caldera.

5 GPS VALIDATION OF THE OBSERVED SUBSIDENCE

Considering both the results obtained from the theoretical studies and from the experimental studies using the SAR technology, it was decided to establish and observe a GPS network of homogeneous density (Fernández *et al.* 2003). The chief objective was to define a new system for the geodetic monitoring of deformation associated with volcanic activity on the island of Tenerife using both techniques, GPS and InSAR. A further basic objective was to validate the deformations determined by InSAR and the GPS network was densified in the northwestern area of the island (Montaña Negra lava flow), to the south of Garachico, where deformation has been detected using InSAR. We selected 17 vertices from the existing network, with accurate coordinates determined by the REGCAN-95 geodetic system (Caturla 1996) plus the permanent station at Santa Cruz de Tenerife (TENE; González-Matesanz & Dalda 2001; Fernández *et al.* 2003). The geographical distribution of the general network vertices can be seen in Fig. 5. The results obtained from GPS observations are described in detail by Fernández *et al.* (2003, 2004). What follows is a summary with some discussion in relation to the results obtained using InSAR.

The data collected during the 2000 survey was processed using BERNESE 4.2 software (Beutler *et al.* 2001) with precise ephemerides. The global network and densification data were processed separately. The results obtained are accurate to 1 cm in height and several millimetres in horizontal coordinates. Comparing 2000 and 1995 coordinates for all the stations, Fernández *et al.* (2003) observe that the network and its densification have an average sensitivity to vertical displacements of approximately 2 cm, with extreme values of 6 and 7 cm. There are no major differences greater than 3 cm and larger than twice σ, where σ is the mean square error of the difference in ellipsoidal height, except at stations Pto. de la Cruz, Retama, Pinar de Chio, Mozos and C747, of the fourth order, in all cases indicating a decrease in the altitude of the station. At the other stations, height concordance is very good.

The height decrease in Pinar de Chío station, 4.9 cm, is of the same order as obtained in the SAR observations in the Chío zone. This subsidence is accompanied by a horizontal disent towards the west

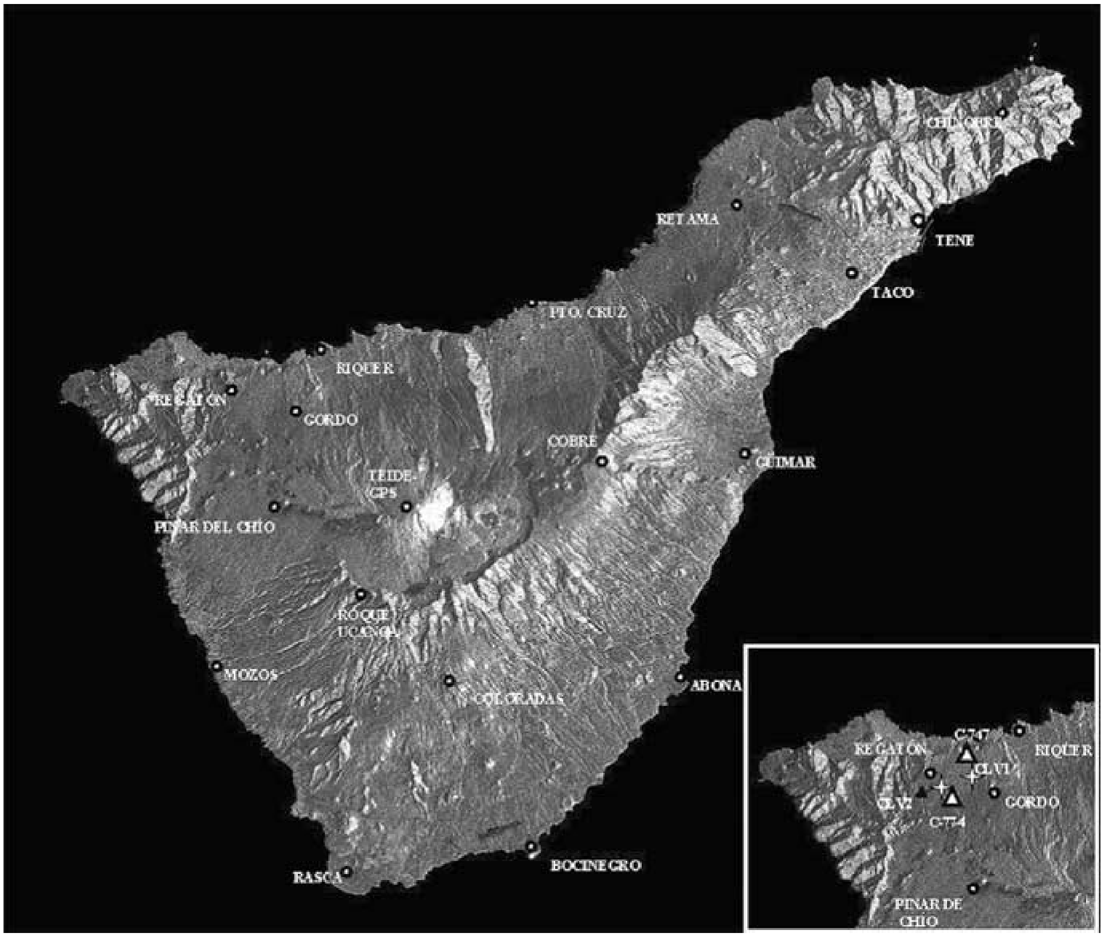


Figure 5. Global GPS network and densification (right lower corner) (after Fernández *et al.* 2003).

of approximately 2 cm. Therefore, to begin with, the GPS results confirm the SAR ones.

The subsidence values found at Puerto de la Cruz station are of greater magnitude, but is most likely a very local deformation. This is confirmed by the observation of several fractures in the breakwater at the port where this station is located (Fernández *et al.* 2003). Radar interferometry does not provide information in this very small zone. Retama station is where the greatest subsidence, 13 cm, is found, together with approximately 3 cm of southerly displacement in the 5 yr between both observations, but this station is located in a zone where, as a result of the existence of dense vegetation, the coherence is null, so no results have been obtained using InSAR. This is an example where GPS and SAR complement one another in monitoring deformations on the island. Mozos station is also located in a zone of very low coherence, so interferometry results are not available there either. The fourth-order station C747 is located on the roof of a small water tank, the height of which is more than likely to vary depending on the level of water in the tank. Therefore, as the variation in coordinates is not significant, it was not used in the following campaigns (Fernández *et al.* 2003, 2004).

The results obtained in the deformation area located to the south of the town of Garachico were not definitive enough to confirm the displacements detected using InSAR. New GPS campaigns were performed in 2001 and 2002 (Fernández *et al.* 2004). The comparison of coordinates between 1995, 2000, 2001 and 2002 is shown in Fig. 6. The comparison of the 2001 and 1995 coordinates at the Pinar de Chío station (Fernández *et al.* 2004) confirmed the subsidence results obtained by InSAR. In addition, horizontal displacements of around 1 cm in the N–W direction are detected. The vertical deformation obtained upon comparing the values of 2000 and 2001 are not significant, as was expected. The horizontal deformation results are significant again in the N–W direction. Comparing the 2002 and 1995 coordinates shows the height values to be quite identical, with differences below precision level. Horizontal displacement is still in the N–W direction, increasing in magnitude to the N and decreasing to the W. If one compares 2002 to 2000, the horizontal displacement is still N–W, but compared with the results for 2001, the displacement is N–E. In short, vertical displacement at the Pinar de Chio station (see Fig. 6) indicates clear subsidence from 1995 to 2000 (coinciding with InSAR results) and elevation from 2000 to 2002.

At the Roque de Ucanca station, upon comparison of the different epochs, we observe a slight subsidence, though not significant above the noise level. The horizontal components display a N–W displacement, as in Pinar de Chío. In the fourth-order pin C774, the vertical coordinate variations in the comparison of 2000, 2001 and 2002 with respect to 1995 were not significant because the 1995 coordinates were not very accurate. Comparison between 2000 and 2001 results are not significant either, but comparing 2002 with 2000 and 2001 values gives clearly significant subsidence. Comparing the 2000 coordinates with 2001 and 2002 reveals horizontal displacement in the S–W direction. Comparing the 2002 and 2001 reveals N–W displacement.

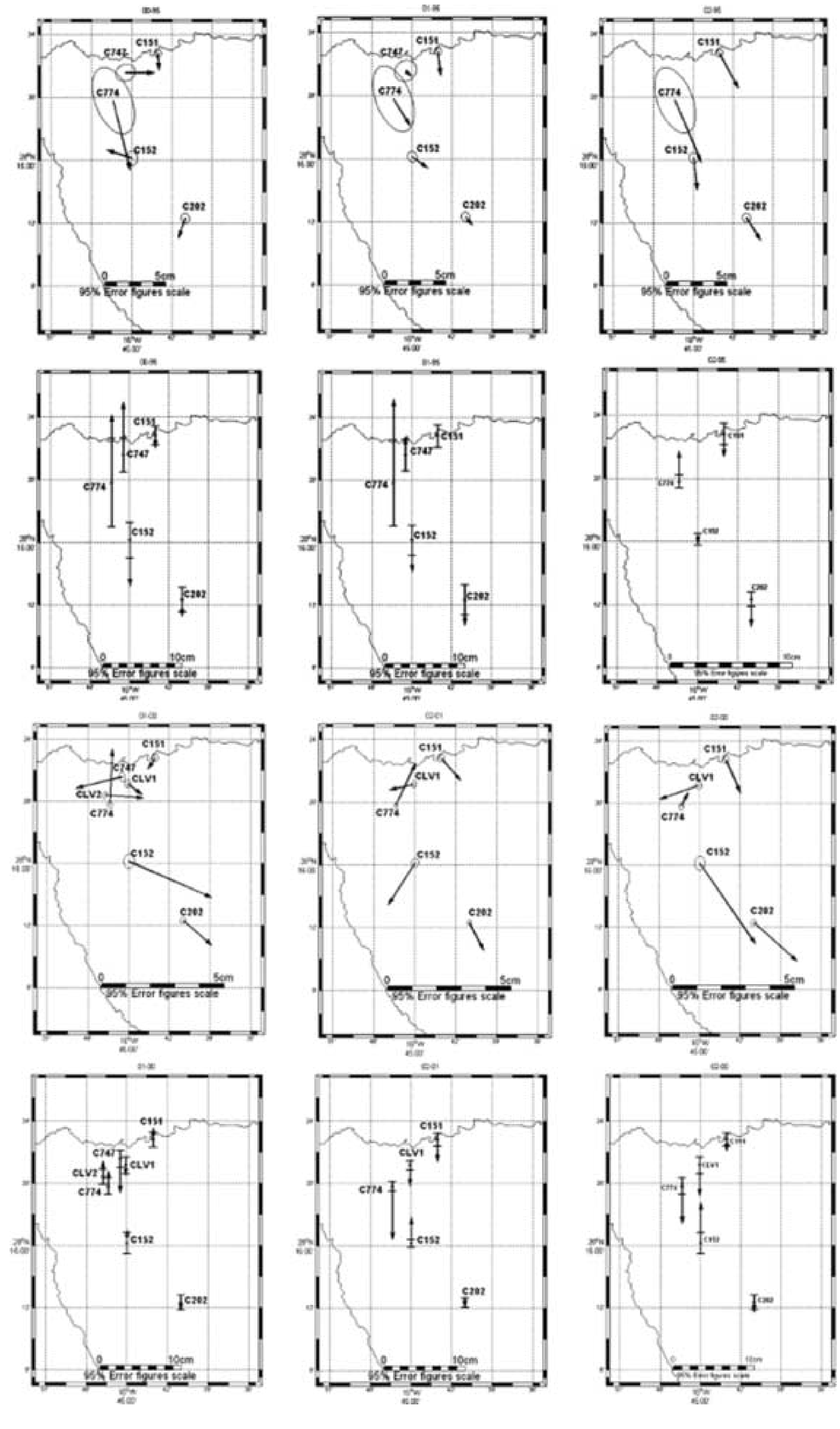


Figure 6. Horizontal and vertical displacement with errors. Vectors with error ellipses for horizontal motions and with error bars for vertical motions. Differences, given in centimetres, are computed by comparison of coordinates measured in 1995, 2000, 2001 and 2002 for the repeated stations of the Deformation Zones (DZs) micronetwork. For example, 00–95 indicates the differences between 2000 and 1995 coordinates. The equivalence between codes and names for the stations where they are different is as follows: C151 = Riquer; C152 = Pinar de Chío; C202 = Roque de Ucanca. (After Fernández *et al.* 2004).

At stations CLV1 and CLV2, comparing the 2001 and 2000 coordinates, the vertical coordinate differences are not significant (Fernández *et al.* 2004). As a result of its disappearance, CLV2 was not observed in 2002. Comparing the 2002 coordinates of CLV1 with the 2000 and 2001 values (see Fig. 5), we observe a clear and significant subsidence with clear horizontal displacement. Station Riquer shows subsidence and a N–W displacement. For further details about the GPS observation and results see Fernández *et al.* (2003) and Fernández *et al.* (2004).

In summary, in the areas where there is coherence and InSAR can be applicable, concordance between InSAR and GPS results is found. Also coordinate variations have been detected in areas where radar observation cannot be used for deformation monitoring as a result of very low coherence. We are talking about maximum displacements between 1 to 2 cm per year during the period 1992–2000 that can be detected using both observation techniques in appropriate conditions. We have shown that, applied properly, the two techniques are complementary and should be combined in any monitoring methodology that is to be efficient in detecting possible deformations associated with volcanic reactivation on the island. Finally, the use of GPS technique will give us information about the 3-D deformation field, not possible to obtain using only InSAR techniques.

6 DISCUSSION AND INTERPRETATION

One important goal of this work was the determination of the possible cause or causes of the detected deformations. In addition, these causes might differ from one area to another. In a volcanic area such as the island of Tenerife, subsidence can be triggered by different natural causes associated with volcanic activity. A first discussion may be seen in Fernández *et al.* (2003), although no one hypothesis is favoured over another. This paper addresses this issue more thoroughly and seeks to ascertain whether the origin might be natural, in particular a magmatic reactivation process, or is related to human activity on the island.

The first possible natural cause linked to volcanic activity is compaction of the lava. Both subsidence locations are in the area where the last eruptions on the island took place (NW–SE dorsal), so one might hypothesize that they are the result of the compaction of the material expelled during such eruptions. Even though a more in-depth study of the area would help to discard it altogether, by calculation of the date when they began to occur (the interferograms obtained show that the subsidence increased from 1992 to 2000, but the exact start is not known as there are no SAR images prior to that date), this cause seems very unlikely to produce the observed deformation almost one century or more after the end of the eruptions.

Another possible cause of the detected subsidence could be that the magmatic chambers collapsed after they were emptied. However, this does not seem a serious candidate for two reasons. First, the fact that the magmatic intrusions in the ridge areas are dykes means that the magma rises directly from the mantle and there are not large chambers in which it can accumulate (Marinoni & Gudmundsson 2000). Secondly, the eruptions took place more than one century ago.

The last possible natural cause could be volcanic reactivation. Taking into account the type of volcanism described above (dyke intrusions), subsidence could be precursor of an eruption if the dyke was close to the surface (Yu *et al.* 2000). In such an event, there would have been a certain amount of seismic activity in the zone, associated with the rise of magma, probably increasing with time. According to the figures provided by the IGN (Blanco, private communication, 2003), there has been no seismic activity in either of the two deformation areas from 1985 to 2003 March with a magnitude of 2.5 or greater (the magnitude threshold of the seismic stations in the island). Nor have the observations conducted in the area detected any clear gas anomalies (Pérez, private communication, 2002). Had there been an intrusion, particularly a shallow intrusion, in one or both zones, one would expect these and other types of geodynamic

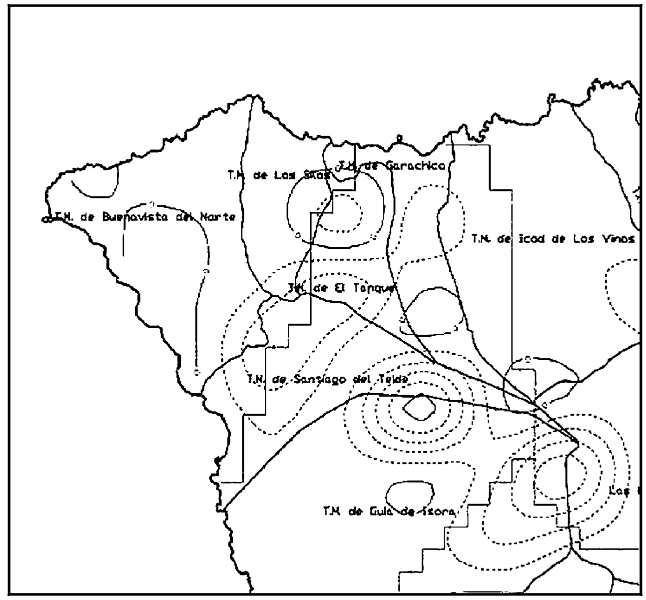


Figure 7. Decreasing underground water level, estimated for the period 1985–2000 in that part of the island including the deformation areas. (Modified from Plano 16 from the Document no. 2 of the graphical documentation of the Plan Hidrológico Insular de Tenerife, http://www.aguastenerife.org/sup.html)

manifestations to have occurred in the last years and this has not been the case.

Therefore, it seems one can discard the hypothesis that natural causes are associated with volcanic activity, although the deformations detected should continue to be researched and observed on a permanent basis, in view of the volcanic nature of the island and the potential risk.

We now consider the possible causes linked to human activity. On the island of Tenerife large amounts of groundwater are pumped out through galleries, boreholes and wells. The water supply in Tenerife comes from underground water located in a general saturated zone, which is extracted through horizontal tunnels (galleries) inland and vertical boreholes and wells on the coast (Gobierno de Canarias, Cabildo Insular de Tenerife, 1989). It is worth noting that the Garachico deformation is in an area scattered with galleries and that the area of the biggest deformation is located at the intersection of several of them. The Chío deformation is not intersected by galleries, but several of them are very close to it. Moreover, both locations, as well as the Retama GPS station, where subsidence of more than 10 cm was detected (Fernández *et al.* 2003), are in those areas of the island where the groundwater level has dropped the most as a result of groundwater extraction, as shown in Fig. 7 (Insular de Consejo/Aguas de Tenerife, 2002).

It is reasonable to consider that the decline in the groundwater level might be at least partly to blame for the deformations described above. This hypothesis is supported by the fact that no evidence has been found for additional widespread activity to justify the appearance of the different subsidence regions detected in large areas scattered around the surface of the island. Nor should one forget that clear examples of surface displacement associated with changes in groundwater levels are being detected, using InSAR and other techniques, in many places around the world (e.g. Massonnet *et al.* 1997; Galloway *et al.* 1998; Amelung *et al.* 1999; Bürgmann *et al.* 2000; Galloway *et al.* 2000; Hoffmann *et al.* 2001; Le Mouélic *et al.* 2002). Another reason to consider this hypothesis is the fact that, since 2000, there has been a clear increase in rainfall on the island (Farrujia, private communication, 2002), as a result of which groundwater levels may have risen in some areas of the island. This would be consistent with the observations at Pinar de Chío station, where via GPS observation it was noted that, after the subsidence from 1995 to 2000 (coinciding with InSAR results), elevation increased from 2000 to 2002 (see Fig. 6).

In order to test this hypothesis, we interpreted the displacements using the model developed by Geertsma (1973) and used in similar problems by different authors (e.g. Xu *et al.* 2001; Le Mouélic *et al.* 2002). We will only consider the vertical component of the displacement in our study, which seeks to establish or discard whether there is any connection between the two phenomena, the deformations observed in the period 1992–2000 and the extraction of groundwater, and to try to model the observed displacement by InSAR. Here the deformation will be considered, to first order, as subsidence. The model assumes that the reservoir is a circular disc of radius R and height h buried parallel to the flat earth surface at depth D. The earth is treated as an elastic half-space with a Poisson's ratio σ.

We want to note the following aspects:

(i) we consider here the possibility that the decline in the groundwater level can be related to the observed displacement, but we do not assume it is the only one origin for them;
(ii) the model is a simple one and does not reproduce totally the real situation on Tenerife Island, therefore it is only a first approximation;
(iii) our objective is to study if the hypothesis (i) looks reasonable after the modelling results.

Thus the vertical component of the displacement of the surface u is (Geertsma 1973)

$$u = (2\sigma - 2)\Delta h R \int_0^\infty e^{-D\alpha} J_1(\alpha R) J_0(\alpha r)\, d\alpha, \qquad (1)$$

where r is the radial coordinate along the surface with an origin above the centre of the reservoir, Δh is the variation of the height of the reservoir as a result of its recharge or compaction and α is the integration variable. For the elastic properties of the reservoir rock, we will consider the parameters determined by Fernández *et al.* (1999). They give as properties for the 3.5 km of crust in their cortical model (from 2 km over sea level to 1.5 km below it) a density of 2100 kg m^{-3} and Lamé parameters $\lambda = 8 \cdot 10^9$ Pa and $\mu = 7 \cdot 10^9$ Pa. Therefore the Poisson's ratio is $\sigma = 0.27$. From the information given by Consejo Insular de Aguas de Tenerife (2002), we obtain an approximation of the depth and radius values of the underground aquifers in order to use the model described. We denote the values for the Garachico deformation area with subindex 1 and the value for Chío deformation area with subindex 2. The obtained results are $D_1 = 0.4$ km, $R_1 = 2$ km, $D_2 = 1.2$ km and $R_2 = 3$ km. Considering these values, we use eq. (1) via the code developed by Le Mouélic *et al.* (2002) to compute the vertical displacement shown in Fig. 8. Comparing the graphics in Fig. 8 with Fig. 3, we observe that a groundwater level decrease of approximately 10 cm below the Garachico deformation area and 4 cm below the Pinar de Chío deformation area is sufficient to produce the maximum value of the observed deformation. Therefore, looking at the results obtained, it seems reasonable to consider that the falling groundwater level caused by water pumping may, in part at least, account for the observed displacement. That is to say, both phenomena are related. The modelled decreasing groundwater level shown in Fig. 7 is also conclusive. The decrease in groundwater level computed using the model is small compared with that interpolated by the Consejo Insular de Aguas, which is of the order of a few metres (Farrujia, private communication, 2004). However, we consider two aspects: (i) that this modelling, performed in 1991, gives only an estimation of the decrease considering the rate of water extracted in that epoch (Farrujia, private communication, 2003); and (ii) that both values are not directly comparable because the actual shape and distribution of the water table, as well as the parameters of the medium, are very different from that considered in either model. We must not forget that the theoretical model employed here is a simplification of the complicated hydrological system of the island and that this modelling is only a first step towards the objectives described above. Future work includes efforts to provide a more detailed model.

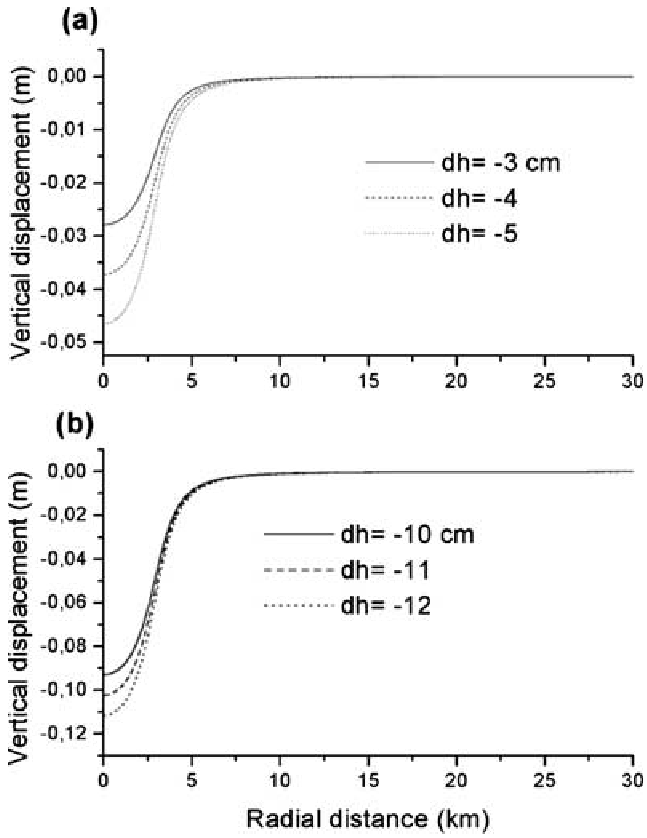


Figure 8. (a) Vertical displacement produced by groundwater level decrease below the Garachico deformation area. (b) The same for the Pinar de Chío deformation area. dh indicates the magnitude of water level variation and the sign minus indicates decreasing.

7 SUMMARY AND CONCLUSIONS

The studies conducted using 18 SAR images covering the years 1992–2000 demonstrate that InSAR can be applied for routine monitoring purposes in Tenerife, because the coherence remains stable over long periods of time and over a large part of the surface of the island.

Our study detected two regions of subsidence that none of the other techniques used in Tenerife had observed. The two deformations are located in the northwest part of the island, one of the zones where the last eruptions took place. Although the subsidence is small in both areas (9.1 cm in the Garachico area and 3 cm in Chío), they cover an extensive area (Garachico 15 km^2; Chío 8 km^2). Furthermore, our results pointing to a lack of deformation in Las Cañadas Caldera match the results obtained with the terrestrial geodetic techniques normally used in that part of the island.

Atmospheric artefacts are present in the interferograms and phase interferences appear as a result of additional components associated with stratification resulting from large height variations. These did not prevent us from detecting the deformations because we used a large data archive with different interferograms covering the same time span also enabling multiple time-series.

The N–E part of the island is harder to monitor with the ERS satellites (which operate in the C band) as a result of the abundant vegetation. The best option at present time is to combine InSAR observation with another technique, GPS, in order to effectively monitor the entire island. We have defined a GPS network that covers the whole island with densification in the deformation zone to the south of Garachico and a station in the middle of the Pinar de Chío deformation zone (Fernández et al., 2003). The whole of the new network was observed in 2000 August, allowing us to validate the deformation obtained in Chío. The two techniques, InSAR and GPS, have been combined to define a new system for geodetic monitoring of possible displacements associated with volcanic reactivation. The densified GPS network covering the two deformation areas was re-observed in 2001 and 2002, allowing for the detection of a rebound in the Pinar de Chío area and additional subsidence in the Garachico zone.

Our goal is to detect, with the combination of both techniques, GPS and InSAR, vertical displacements on the order of 1–2 cm yr^{-1}, taking into account the results obtained using InSAR and GPS in the time period 1992–2000. We have shown that both techniques are able to detect that magnitude of displacement. For the GPS campaigns, this is described by Fernández *et al.* (2003, 2004). For radar interferometry, the temporal sampling is related to the deformation rate, so that it is more useful to discuss the absolute deformation and number of interferograms. Practically, we could detect 1–1.5 cm after 1 yr of continuous imaging over the same area (between 5 and 10 images); e.g. this is in line with the detection of Chío deformation after 8 yr. GPS observations should give the 3-D deformation field, but for only a few points in the island (20 stations if we consider global GPS network and densification). The use of GPS allows for the collection of deformation data in the parts of the island where there is no coherence and therefore InSAR is not applicable. In the areas where there is good coherence, InSAR should give us a much better spatial resolution. This fact is really important if we want to discriminate between deformation patterns produced by different sources (e.g. water table level variation versus dyke intrusion). In the case of volcanic reactivation, it would be necessary to include permanent GPS observation in this network in order to give continuous temporal observations.

A first attempt has been made to interpret the subsidence using a simple theoretical model (Geertsma 1973) that can only be regarded as a rough approximation to the real problem on the island of Tenerife, as a result of both the type of reservoir and the medium considered (homogeneous and without fractures). However, there is clearly a need to continue with this research, with further monitoring of the displacements in order to study their evolution, and further interpretation, including the examination of an additional type of geophysical data (gravity, gases, etc), with detailed and up-to-date information about the evolution of the groundwater, and the development of models that represent the characteristics of the island more accurately.

Finally, it must be stressed that this research is very important, not only for the study of displacements that might be associated, at least in part, with the extraction of groundwater, but also because it underscores that the volcanic monitoring system in the island must be capable of clearly distinguishing them from other displacements on the surface of the island that might be linked to a future magmatic reactivation. Doing so entails having a technique with the highest possible spatial resolution and sufficient precision in the geodetic monitoring. InSAR is one such technique. If the C band is used in radar observation, InSAR would have to be combined, for example, with GPS, with a dense enough network of stations, in the NE part of the island, to overcome the coherence loss problem posed by the dense vegetation. The ideal solution would be to use InSAR in the L band, which could be used to obtain a displacement map (with lower sensitivity but vegetation independent), albeit with the current limitation of still not having the three components of deformation. In this case, a complementary GPS observation would not need to be so dense. Furthermore, it is clear that measuring displacements is only one part of an effective volcanic monitoring system, which will include other techniques such as gravimetry, seismology and gas observation, to name only a few.

ACKNOWLEDGMENTS

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